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PART I

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SIMULATION OF TURBOFAN ENGINE

PART I. DESCRIPTION OF METHOD AND BALANCING TECHNIQUE

JOHN S. McKINNEY, CAPTAIN, USAF

TECHNICAL REPORT AFAPL-TR-67-125, PART I

JAN 1968

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AIR FORCE AERO PROPULSION LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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NOTICE

[redacted]

patented invention that may in any way be related thereto.

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AFAPL-TR-67-125
PART I

SIMULATION OF TURBOFAN ENGINE

PART I. DESCRIPTION OF METHOD AND BALANCING TECHNIQUE

JOHN S. McKINNEY, CAPTAIN, USAF

[redacted]

FOREWORD

This report was prepared in the Components Branch (APTC), Turbine Engine Division, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, under Project 3066, "Gas Turbine Technology," Task 306603, "Advanced Engine Studies," with Charles E. Bentz as Project Engineer.

This report covers work conducted within the Components Branch in the time period between July 1965 and June 1967 and was submitted by the author 31 August 1967.

This technical report has been reviewed and is approved.

Ernest C. Simpson

ERNEST C. SIMPSON
Chief, Turbine Engine Division
Air Force Aero Propulsion Laboratory

ABSTRACT

This report describes a digital computer program titled SMOTE (Simulation of Turbofan Engine). SMOTE is a computer program for balancing-cycle turbofan engines capable of running both design and off-design points. Component performance maps are reduced to Block Data (tabular form) to provide a base for calculating component performance. The design point is run first and map correction factors are calculated to scale the components to the desired performance. These correction factors are then applied to the component performance maps at off-design points. Initially, when the program is running at an off-design point, the cycle is not balanced, and errors (for example, work required by the compressor minus work supplied by the turbine) are generated. Small changes in engine independent variables (for example, compressor speed) then produce small changes in the errors, and these differential changes are loaded into a matrix. The matrix is then solved for the set of independent variables which results in zero errors, thus balancing the cycle. Actually, this process may be repeated several times before it reaches a balanced point because there is a nonlinear relationship between the independent variables and the errors. Sample results are included in this report.

(Distribution of this abstract is unlimited.)

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ILLUSTRATIONS

SYMBOLS

BLF	bleed from fan lost to cycle (leakage)
BLDU	bleed from compressor to duct (leakage)
BLHP	bleed from compressor to high pressure turbine (cooling)
BLLP	bleed from compressor to low pressure turbine (cooling)
BLOB	bleed from compressor overboard for customer use
CN	corrected speed
DHTC	delta-H corrected for temperature
H	enthalpy
PCNC	percent speed of the compressor
PCNF	percent speed of the fan
P	pressure
P2	pressure at the fan face
TFFHP	turbine flow function, high pressure turbine
TFFLP	turbine flow function, low pressure turbine
T	temperature
T2	temperature at the fan face
T21	temperature at the fan exit
T4	main combustor burning temperature
T24	duct-burner burning temperature
T7	afterburner burning temperature
WFA	afterburner fuel flow
WFB	main-combustor fuel flow
WFD	duct-burner fuel flow
WG	gas flow rate
ZC	pressure-ratio ratio of the compressor
ZF	pressure-ratio ratio of the fan

SECTION I

INTRODUCTION

Recent advances in turbine-engine state of the art have increased the requirements for more and better cycle studies. These cycle studies are needed to monitor present engines, determine sensitive or critical areas in near future engines now under development, and to explore the advantages and disadvantages of proposed advanced engine cycles for future aircraft.

Parametric cycle studies, which involve essentially numerous design-point calculations, partially fulfill this need, particularly for optimizing a cycle for a specific single design-point mission. However, with multimission aircraft being emphasized increasingly and with the need for determining off-design performance, the requirement for a balancing cycle computer program (that is, one which simulates a turbine engine at both design and off-design points) becomes definite and essential.

The purpose of this report is to describe a digital computer program for balancing-cycle turbofan engines. The program, titled SMOTE (Simulation of Turbofan Engine), was developed in the Components Branch, Turbine Engine Division Air Force Aero Propulsion Laboratory, to meet the requirements given in the preceding paragraphs. In addition to meeting these requirements, SMOTE is considerably more flexible, requires less computer storage or space, and requires less computer operating time than previous engine cycle decks of comparable sophistication.

Part I of this report describes the method of engine calculations and the balancing technique and gives some sample results. Part II is intended as a user's manual and includes instructions for setting up and running the program, as well as a program listing. The parts may be used independently of one another.

SECTION II

SUMMARY

SMOTE is a computer program for balancing-cycle turbofan engines which presently uses component performance maps for the fan, compressor, combustor, and both turbines to provide the basic performance data, but it can easily be expanded to include additional component performance maps if available. The maps are in Block Data form and are scaled internally to simulate a specific engine. Errors due to an unbalanced cycle are generated at off-design points, and the effects of small changes in independent variables upon the errors are determined. A matrix of differential error equations is then solved to determine the correct values of the independent variables which would produce zero errors. A flow chart of the program is shown in Figure 1.

For a more accurate simulation of a particular engine, performance maps for other components could be added; for example, duct-burner or afterburner maps may be desired. It should also be mentioned that other formats for presenting maps may be used as readily as those presented in this report. Rather than inputting bleed air values at each point or using a constant bleed, a bleed schedule could be used. In addition, if a variable-area nozzle is to be simulated, a nozzle area schedule could be used. Or an engine control system could be used which would set fuel flow, bleeds, and nozzle areas as some function of a power lever angle.

The complexity of an engine cycle can be increased by increasing the size of the matrix (increasing the number of partial differential equations). For example, a basic triple-spool turbofan cycle could be represented using a matrix of nine equations. Or a T-compressor fan engine composed of a fan tip, fan hub, low pressure compressor (running at the same speed as the fan), high pressure compressor, combustor, two turbines, gas mixer, and afterburner could be represented using a matrix of eight equations.

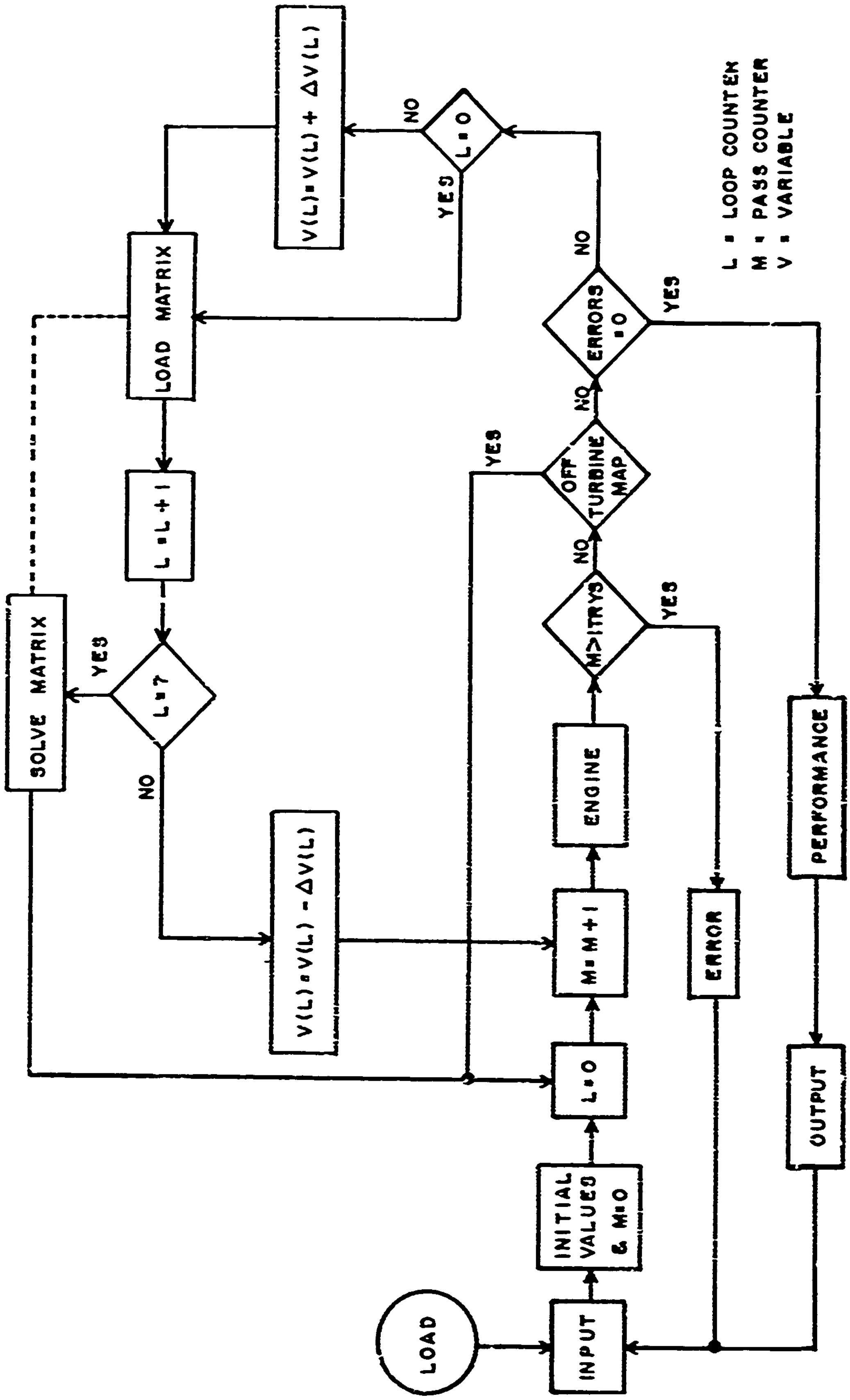

Figure 1. SMOTE Computer Program Flow Chart

SECTION III

HISTORY

Until about six years ago, most general cycle calculations in the Components Branch were done by hand, although some computer programs were available for specific engines. About that time a turbojet, parametric-cycle study program (SPEEDY) was conceived, and, from this program, a more general turbojet or turbofan program (CARPET) with many configuration options was developed. CARPET is still in general use for parametric and optimization studies.

About three years ago, a balancing-cycle turbojet or single-spool computer program (SSPOOL) was developed within the Components Branch. The engine component calculations were based essentially on those in CARPET, and the balancing technique, which depended upon a quadratic interpolation routine (AFQUIR), involved two nested balancing loops. The inner loop was balanced using PCNC as an independent variable and the work difference between compressor and turbine as the dependent variable. The outer loop was balanced using ZC (see Figure 2 for a definition of ZC) and the pressure required by the fixed-area exhaust nozzle. After the inner loop was balanced, the outer loop was changed in an attempt to balance it. Naturally, changes in the outer loop necessitated rebalancing the inner loop. This method, although rather crude, worked well for a turbojet cycle.

The SSPOOL concept was then extended to a turbofan or dual-spool cycle which resulted in a new program called DSPOOL. By logical extension this required four nested loops with four independent variables (PCNF, ZF, PCNC, and ZC) and four dependent variables or errors (two work errors and two nozzle pressure errors for a separate flow cycle; or two work errors, a mixing static pressure error, and a nozzle pressure error for a mixed flow cycle). Although the method worked, computer time was excessive, and various techniques (such as changing the order of the independent variables or using a varying tolerance) were tried in an attempt to shorten the balancing time. These attempts were only partially successful.

Other balancing techniques using various mathematical solutions were experimented with, and the present method was finally developed. This method involves no nested balancing loops; instead, a matrix is loaded with differential errors caused by small changes in the independent variables. The matrix is then solved for the zero error condition. SMOTE reduced computer time by an average factor of about 4 as compared to DSPOOL.

SECTION IV

METHOD OF ENGINE CALCULATIONS

1. COMPONENT MAPS

The performance of the major engine components is based on component maps. These maps are usually obtained from analytical methods or rig-testing and are then converted into Block Data subroutines for use by SMOTE. The maps presently included in SMOTE are very general and do not represent any particular engine or engine components.

The component maps are scaled at the engine design point by SMOTE in order to match their performance to a desired set of performance figures which are input as data. Scaling or correction factors are calculated and then applied to the maps at off-design points. The scaling process is linear; therefore correction factors near unity result in the highest accuracy of component simulation. This means that the component maps used should represent or be similar to the actual components in the engine being simulated. However, with the loss of a little accuracy, maps representing advanced components could be interchanged to determine the effect on the overall cycle.

SMOTE presently includes component maps for the fan, compressor, combustor, and both turbines. Duct burning, duct losses, gas mixing, afterburning, tailpipe losses, and nozzle losses are all calculated or input, but these characteristics could also be included as Block Data if maps were available. Likewise, schedules for bleed air and variable area nozzles could be used.

a. Fan-Compressor Maps

The fan and compressor maps are very similar and are plots of corrected airflow versus pressure ratio with constant corrected speed lines and constant efficiency islands (see Figure 2). Entry to the map is through the corrected speed and Z, where Z is a pressure-ratio ratio, and is defined at a constant corrected speed as shown in Figure 1. It is advantageous to use Z instead of pressure ratio because Z is restrained between the limits of 0 and 1, whereas the limits on the pressure ratio vary depending upon map location and the particular map. Also, an indication that the fan or compressor is approaching surge is given as Z approaches 1.

b. Combustor Map

The combustor map is a plot of temperature rise across the combustor versus efficiency for constant input pressure (see Figure 3). Entry to the map is through temperature rise and input pressure, with efficiency being output.

c. Turbine Map

The turbine map is a plot of turbine corrected speed versus work function with constant turbine flow function lines and constant efficiency islands (see Figure 4). The work function and flow function are defined as

$$DHTC = \frac{H_{IN} - H_{OUT}}{T_{IN}}$$

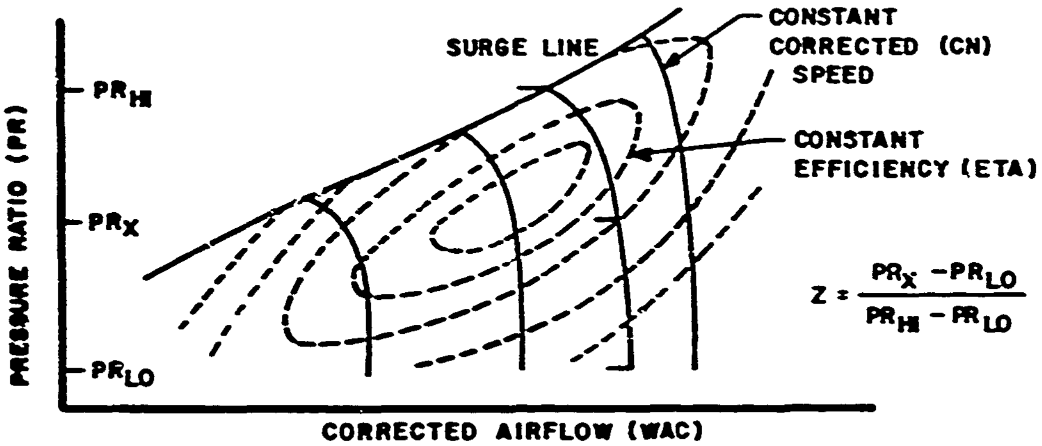

Figure 2. Example of Fan-Compressor Map

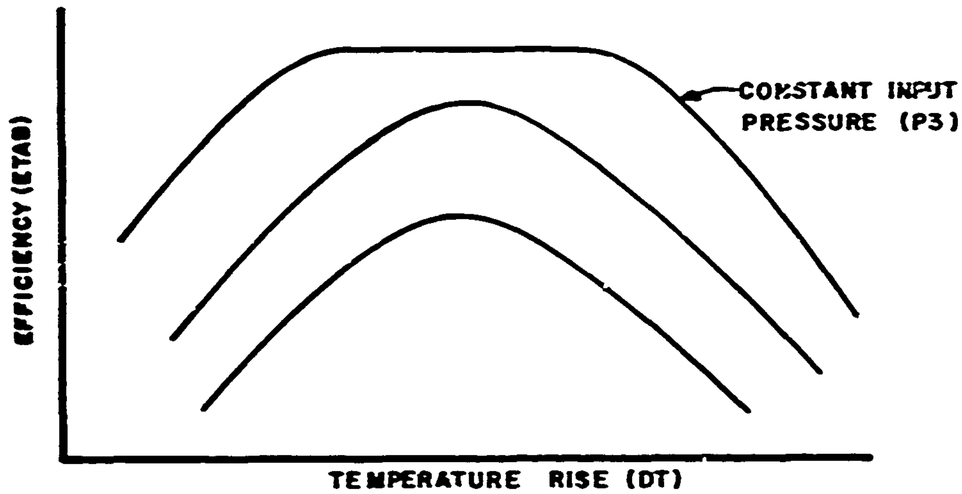

Figure 3. Example of Combustor Map

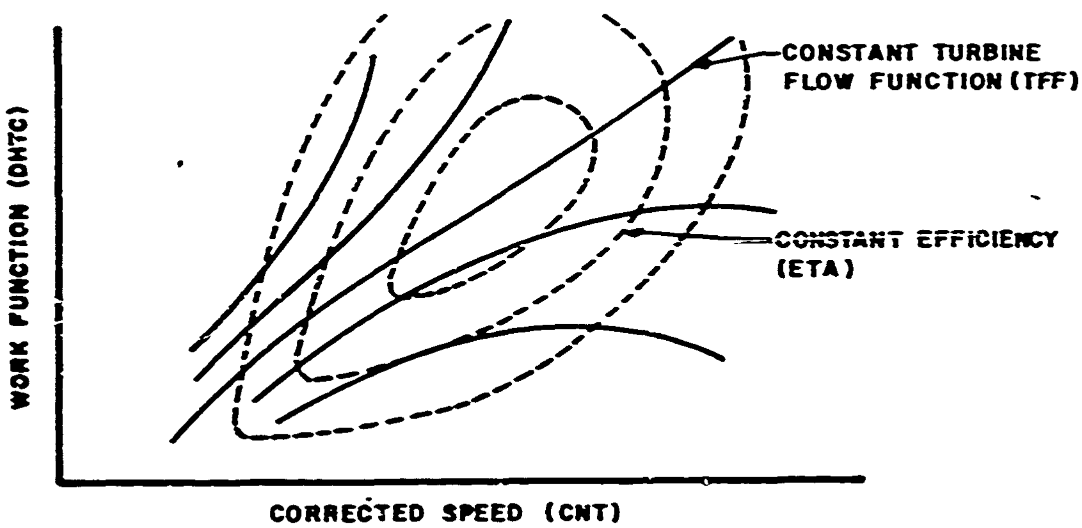

Figure 4. Example of Turbine Map

and

$$TFF = \frac{WG_{IN} \sqrt{T_{IN}}}{P_{IN}}$$

Entry to the map is through corrected speed and turbine flow function, with the work function and efficiency being output.

The work function could have been used as an entry in place of one of the present entries, but, because of the shape of the curves, this could lead to double entry points for one work function. However, if the turbine maps were plotted in a different format, this could be an acceptable method.

2. DESIGN POINT

Once the component maps have been reduced to Block Data form and placed in the program, it is necessary to run a design point. The design point is run at those conditions under which the real engine is designed or sized, usually sea level static. Design parameters necessary to simulate the real engine (for example, airflow, bypass ratio, main burner temperature, various pressure losses, pressure ratios, etc.) are input and a complete thermodynamic cycle calculation is performed. For more details on the cycle calculation see Section IV 4, "Off-Design Points." Scale factors for the component maps are calculated to insure that the input design parameters are met. If the design parameters have been correctly input, the design point will be completed after one pass through the engine calculations (that is, no balancing will occur) because the maps are shifted to reduce the errors to zero.

Other parameters calculated and output at the design point include certain temperatures and airflows, gas mixing areas, and nozzle throat and exit areas.

3. SCALING FACTORS

Scaling or correction factors are calculated at the design point using the following equation:

$$P\,(\text{correction factor}) = P\,(\text{design}) \,/\, P\,(\text{map})$$

where P represents a general parameter. One exception to this equation is the equation for calculating fan and compressor pressure correction factors:

$$PR\,(\text{correction factor}) = \left[PR(\text{design}) - 1\right] / \left[PR\,(\text{map}) - 1\right]$$

where PR represents a general pressure ratio.

Theoretically, if the component maps and the input design parameters are exact representations of a particular engine, the correction factors will equal 1. However, this will not be true due to map interpolations, certain assumptions such as ideal and isentropic flow, and tolerances in the thermodynamic calculations. The correction factors should be within 1% of 1. Naturally, if unmatched component maps are used, the correction factors can differ significantly from 1.

4. OFF-DESIGN POINTS

The following discussion pertains particularly to off-design points, although the input and the general cycle calculations are the same for the design point. Throughout the following discussion, it should be remembered that scaling or correction factors (multipliers) are applied to all performance maps (Block Data parameters).

For more detailed information on the thermodynamic equations used throughout the cycle calculations, see References 1, 2, and 3 and Part II of this report. A schematic diagram of the engine components and station designations is shown in Figure 5.

a. Input

The program uses a controlled output; that is, the variables desired as output can be selected at the start of a run. This selection is obtained by placing the names of the variables in the first section of input cards. Controls, scaling or correction factors, and operating conditions make up the rest of the input.

The control inputs are used to determine the type of engine: mixed flow or separate flow, afterburning, duct burning, and convergent or convergent-divergent nozzle. The controls are also used to fix the mode of operation: constant PCNC, constant T4, or constant WFB. Other controls determine inlet conditions, title printout, and cycle looping printouts. The correction factors can be input directly, or the design point can be run first and the calculated factors will be left in common. The operating conditions include the flight Mach number, altitude, power setting (either PCNC, T4, or WFB), duct burner and afterburner temperatures or fuel flows, bleed, and horsepower extracted.

b. Initial Values

The program uses four primary independent variables: ZF, PCNF, ZC, and PCNC (T4 may be substituted for PCNC, depending upon the mode of operation). Two secondary independent variables (TFFHP and TFFLP) are also used to insure correct entry into the turbine maps. Initial values for these six variables must be obtained to start the program at each point. A subroutine supplies these variables as a function of T2, T21, and some of the variables themselves. It is important to note that the closer the initial values are to the final values at a balanced point, the faster the program will run. Therefore, after a particular engine configuration has been run a few times, it is usually advisable to change the general initial value equations to suit the engine, using the knowledge gained from past runs to estimate more closely the final values of the variables.

c. Inlet

The thermodynamic properties of the atmosphere are found from a 1962 ARDC Atmosphere Tables subroutine. Using conservation of energy and isentropic flow, the conditions at the face of the fan can be found. A ram recovery (total pressure recovery) can be input or, if not input, a ram recovery defined by Mil-E-5008B Specifications will be used. If desired, a T2-P2 direct input mode is available, as are provisions for nonstandard day conditions.

d. Fan and Compressor

Block Data is used to determine the performance characteristics of the fan and compressor. When Z and PCN are known, the pressure ratio, corrected airflow, and efficiency can be found by using a general Block Data interpolation routine named SEARCH. With the pressure ratio known and when the assumption of isentropic compression and the efficiency are used, the thermodynamic conditions at the exit of both the fan and the compressor can be calculated. Bleed for consumer use, leakage, or cooling is accounted for. Actual airflow leaving the fan and the compressor is calculated from the corrected airflow, temperature, pressure, and bleed.

e. Combustor

The pressure drop in the combustor is a function of a design pressure drop and the ratio of corrected airflow to the design corrected airflow. Combustor efficiency is obtained from

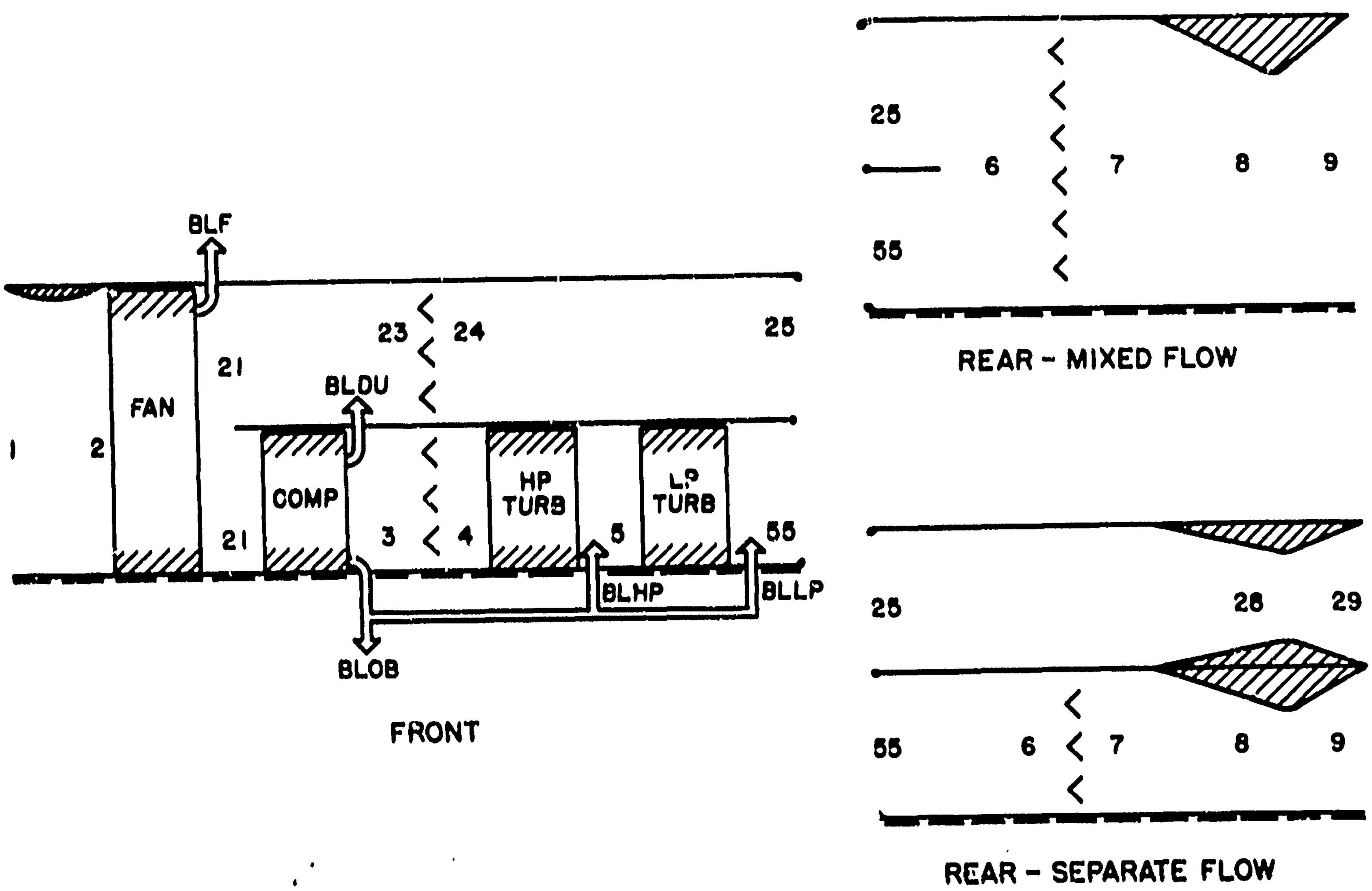

Figure 5. Schematic of Engine Components

Block Data using SEARCH. The fuel used is assumed to be JP-4 (at 59°F), and, with the assumption of adiabatic and constant pressure combustion, a fuel heating value equation as a function of T4 has been derived. Thus the fuel/air ratio, fuel flow, and thermodynamic conditions at the combustor exit can be calculated. If WFB is known instead of T4, a small iteration is necessary.

f. Turbines

Both turbine subroutines use similar logic and obtain their performance characteristics from Block Data using subroutine SEARCH. All three turbine parameters (CN, TFF, DHTC) can be calculated before entering the turbine map, but only two are needed. Therefore, the third parameter obtained from the map is compared with the calculated third parameter, and a balancing error is generated if they are not equal. In this program, CN and TFF are used for map entries, and DHTC is used to generate the error. In addition, the efficiency is also obtained through SEARCH.

In addition, another error will be generated if TFF is not within map limits. The error will be the difference between TFF and the nearest map limit. This error becomes particularly important when the estimated initial values of the independent variables are far from the correct values, and the point is extremely unbalanced. When either TFF or CN is not within map limits, they are set to the nearest map limit, and one of the independent variables is changed in an attempt to rectify the situation. The operating point must appear on all maps before a complete cycle calculation can be accomplished.

Horsepower extraction is accounted for in calculating DHTC of the high pressure turbine. When the efficiency is used and the turbine process is assumed isentropic, the thermodynamic properties at both turbine exits can be calculated. Any bleed airflow for cooling the turbines is treated as if it entered the main stream behind the turbine, and the thermodynamic properties at the turbine exits are recalculated to account for this.

g. Duct

The duct airflow and bypass ratio are calculated from the fan and compressor airflows. The pressure drop in the duct is treated as in the main combustor. For duct-burning, the same fuel heating value equation that was used in the combustor is again used, but the efficiency must be input. As in the combustor, either the temperature (T24) or the fuel flow (WFD) may be input.

If a separate flow engine is being simulated, the duct nozzle calculations are done in this routine, although they are accomplished in the same manner as for the main nozzle.

h. Mixer

The gas mixing areas (duct exit and turbine discharge for a mixed flow engine or just the turbine discharge area for a separate flow engine) are calculated at the design point using either an input static pressure or Mach number. At an off-design point the areas are used to calculate static pressures and Mach numbers.

For a separate flow engine, the thermodynamic conditions entering the afterburner are now known, since they are identical to turbine discharge conditions.

For a mixed flow engine, a set of derived equations based on one-dimensional fluid flow theory and conservation of mass, energy, and momentum is used to determine the thermodynamic conditions after complete mixing of the two gas streams (Reference 4). These equations do not require that the static pressures of the two entering streams be equal. However, for a correct engine balance, the two static pressures must be equal, and a balancing error is generated if they are not equal.

i. Afterburner

The dry loss (cold loss) pressure drop in the afterburner is a function of a design pressure drop and the ratio of corrected gas flow to the design corrected gas flow.

For afterburning, the same equation for the fuel heating value that was used in the combustor is again used, but the efficiency must be input. As in the combustor, either the temperature (T7) or the fuel flow (WFA) may be input. A momentum loss (hot loss) pressure drop is also calculated.

j. Nozzle

The main nozzle program uses fixed effective areas (except when afterburning) calculated at the design point. Either a convergent or a convergent-divergent subroutine may be used depending upon the input controls. If afterburning has been selected, the nozzle areas are allowed to float to obtain optimum performance; however the areas are returned to their original design values after the afterburning point is completed. The duct nozzle behaves identically with the main nozzle, including floating areas if duct-burning has been selected.

Because all thermodynamic properties of the gas stream are known, as well as the amount of flow, nozzle areas, and ambient pressure, there is a redundant parameter. For this program, the total pressure of the gas stream was chosen as the redundant parameter. The nozzle calculations (Reference 5) are made without using the total pressure, and a required total pressure compatible with all other known parameters is calculated. This required pressure is compared with the actual pressure, and a balancing error is generated if they are not equal.

k. Performance and Output

At this point, six errors have been generated after one pass through the engine. Several more passes must be completed under control of the error matrix and engine balancing subroutines. See Section V for a detailed description of the balancing technique used. Eventually, however, the errors will be reduced to zero, and engine performance will be calculated using standard equations. Gross thrust is obtained by summing the momentum term (a nozzle velocity coefficient may be input) and pressure-area term, and net thrust is in turn found by subtracting a ram drag (airflow momentum loss at inlet) term from the gross thrust. Specific fuel consumption is total fuel flow divided by net thrust.

As previously mentioned, a controlled output is used, whereby only selected variables are printed. Each variable is labeled with its name, and provisions have been made for changing the name of a variable. In addition, the values of all variables in common are printed in a close format so that variables other than those selected for a specific run are available later on.

5. QUADRATIC INTERPOLATION ROUTINE

Throughout the program there are many small loops (for example, thermodynamic iterations and table look-up) which require convergence. Trial-and-error methods and linear interpolations can be time-consuming, especially when a tight tolerance is necessary; therefore a general interpolation routine called AFQUIR (Air Force Quadratic Interpolation Routine) was developed.

This routine requires a dummy array dimensioned for nine locations. Also input into the routine through the calling argument are the independent and the dependent variables, the answer or value which the dependent variable is to converge upon, the number of tries at convergence, the tolerance, and a variable called DIR.

The DIR is either set or calculated in the calling program and is an initial guess at the direction and percentage change to apply to the first value of the independent variable. If not enough is known about the variables to calculate a DIR, an arbitrary value may be set. This should not affect the final result, but may increase the number of tries at convergence.

The DIR thus establishes the second value of the independent variable. This value is used in the calling program to determine a corresponding second value of the dependent variable and AFQUIR is called a second time with two sets of values. A linear interpolation is made which results in a third value of the independent variable. AFQUIR is then called a third time with the third values of independent and dependent variables and a quadratic interpolation is made. The values of these three sets of variables have been stored in the dummy array, and from here on, quadratic interpolations are made using the three sets which give values closest to the answer. Values farthest from the answer are lost.

Various safeguards are built into AFQUIR to return the interpolation method to DIR or linear if the roots of the quadratic become complex, if the quadratic does not intercept the answer, if the value of the independent variable differs radically from previous values, or if two sets of independent and dependent variables are identical.

Also, it is possible to preload the dummy array and to start directly at the linear or quadratic interpolations if desired.

In summary, AFQUIR is a completely flexible routine which performs quadratic interpolation for quick convergence of general functions.

SECTION V

BALANCING TECHNIQUE

The balancing technique is based upon finding a solution for a set of partial differential equations. For this program, the set is composed of six equations; however, using a set of only three equations will simplify the following discussion. This corresponds to a basic turbojet engine simulation. It is relatively easy to expand the set of three equations to one of six, as required in SMOTE, or even further. For example, a triple-spool turbofan would require nine equations.

As discussed previously, six independent variables were selected (ZF, PCNF, ZC, PCNC or T4, TFFHP, and TFFLP). Once these variables have been given initial values, it is possible to proceed through an entire engine cycle calculation. Six errors are generated as shown in Section IV. These initial values of the six variables and six errors are referred to as base values.

In the following equations, V refers to a variable and E to an error. The basic set of differential equations based on E = f(V) is (Reference 6)

$$dE_1 = \frac{\partial E_{11}}{\partial V_1} dV_1 + \frac{\partial E_{12}}{\partial V_2} dV_2 + \frac{\partial E_{13}}{\partial V_3} dV_3$$

$$dE_2 = \frac{\partial E_{21}}{\partial V_1} dV_1 + \frac{\partial E_{22}}{\partial V_2} dV_2 + \frac{\partial E_{23}}{\partial V_3} dV_3$$

$$dE_3 = \frac{\partial E_{31}}{\partial V_1} dV_1 + \frac{\partial E_{32}}{\partial V_2} dV_2 + \frac{\partial E_{33}}{\partial V_3} dV_3$$

where the single subscripts correspond to three variables and three errors and where the double subscripts indicate the change in a particular error (first subscript) due to a change in a particular variable (second subscript).

Assuming small changes results in the following approximations (where B refers to a base value):

$$dE = E - EB$$

$$dV = V - VB$$

$$\frac{\partial E}{\partial V} = \frac{\Delta E}{\Delta V}$$

With these approximations and the fact that E should be zero when the engine is balanced, the set of partial differential equations reduces to

$$E_1 - EB_1 = \frac{\Delta E_{11}}{\Delta V_1} dV_1 + \frac{\Delta E_{12}}{\Delta V_2} dV_2 + \frac{\Delta E_{13}}{\Delta V_3} dV_3 = -EB_1$$

$$E_2 - EB_2 = \frac{\Delta E_{21}}{\Delta V_1} dV_1 + \frac{\Delta E_{22}}{\Delta V_2} dV_2 + \frac{\Delta E_{23}}{\Delta V_3} dV_3 = -EB_2$$

$$E_3 - EB_3 = \frac{\Delta E_{31}}{\Delta V_1} dV_1 + \frac{\Delta E_{32}}{\Delta V_2} dV_2 + \frac{\Delta E_{33}}{\Delta V_3} dV_3 = -EB_3$$

Three more passes (six for SMOTE) are now made through the engine cycle calculations, and one variable is changed by a small amount (ΔV) for each pass. The change in each error due to the small change in the variables ($\Delta E/\Delta V$) can then be calculated.

The above set of differential equations can now be solved for dV_1, dV_2, and dV_3, and, in general, the new value of each independent variable would be given by

$$V = VB + dV$$

If the engine cycle calculations were linear functions, the engine would balance (errors equal zero) with these new values of the variables. However, this is not the case, and it is usually necessary to repeat the above process (where the new values become the base values) several times before a balance is obtained.

A subroutine to determine the solution of a matrix is used to solve the set of differential equations. After each pass through the engine, a matrix array is loaded with the appropriate values; after seven passes (base value plus six independent variables), the matrix subroutine is called to solve the matrix.

It was found that the "dV's" obtained from the solution of the differential equations were in many cases too large, thus causing the variables to exceed their limits, and to make it practically impossible to balance the cycle. The "dV's" are therefore multiplied by a suppression factor (presently 0.6) which limits the swing of the variables. In addition, if a suppressed "dV" is still greater than 5% of the value of the variable itself, it is reduced to the 5% value. Although this procedure may tend to increase the number of passes before balancing in some cases, it also balances points which previously would not balance. These points are most generally far from the design point, where oscillations of the dependent variables tend to build up.

APPENDIX

SAMPLE RESULTS

The following computer printouts are examples of typical output from SMOTE. The first point is the design point and includes a page of correction (or scaling) factors and a page of values of variables in common. The other points represent conditions throughout a flight envelope and consist of a primary page of output for each point. Not included for these points is a common dump, which normally follows each primary output page and is very similar to the common dump following the design point correction factors.

The engine cycle chosen was a mixed flow turbofan (bypass ratio of 1.4) with a convergent nozzle, a total airflow of 180 pounds a second, and a turbine inlet temperature (T4) of 2400°R. The points were run in a fixed T4 mode; that is, PCNC is an independent variable. Note that the nozzle area is recalculated at each afterburning point for optimum expansion and that no balancing occurs at these points.

```
                                        SHOTE DESIGN POINT
FAN DESIGN               PRFCF= 0.10000007E 01 ETAFCF= 0.09999999E 01  WAFCF= 0.10000003E 01   T2DS= 0.51866820E 03
COMPRESSOR DESIGN        PRCCF= 0.99577639E 00 ETACCF= 0.10000494E 01  WACCF= 0.99738885E 00  T21DS= 0.65224932E 03
COMBUSTOR DESIGN        WA3CDS= 0.13772873E 02 ETABCF= 0.09999999E 01 DTCOCF= 0.10178453E 01
H.P. TURBINE DESIGN     CNHPCF= 0.99939181E 00 TFHPCF= 0.10000931E 01 ETHPCF= 0.99999999E 00 DHHPCF= 0.10004254E 01
L.P. TURBINE DESIGN     CNLPCF= 0.10003261E 01 TFLPCF= 0.10006253E 01 ETLPCF= 0.09999999E 01 DHLPCF= 0.99003777E 00
DUCT DESIGN             WA23DS= 0.13542101E 04
TURBINE/DUCT AREA DESIGN   A55= 0.20619559E 01   AM55= 0.41298576E-00    A25= 0.42450554E 01   AM25= 0.17414913E-00
AFTERBURNER DESIGN      WO6CDS= 0.30173258E 04
NOZZLE DESIGN               A8= 0.27960084E 01    AM8= 0.09999999E 01     A9= 0.27960084E 01    AM9= 0.09999999E 01
MAIN SONIC CONVERGENT NOZZLE        FG=  8314.55                FN=  8314.55                 SFC= 0.61205
```

```
CONVERGED AFTER   1 LOOPS


COMMON          0.833333E 00  1.000000E 02  0.814598E 00  1.000000E 02  0.240000E 04  0

   0.100000E 03  0.100000E 03  0.240000E 04  1.000000E 02 -0.000000E-19  0.100000E 01  0.100000E 01  0.100000E 01
   0.833333E 00  0.100000E 03  0.200000E 01  0.850000E 00  0.180000E 03  0.100000E 01  0.100000E 01  0.100000E 01
   0.814598E 00  0.100000E 03  0.600000E 01  0.830000E 00  0.750000E 02  0.995776E 00  0.100005E 01  0.997389E 00
   0.240000E 04 -0.000000E-19  0.126000E 04  0.985000E 00  0.137729E 02  0.500000E-01  0.101785E 01  0.100000E 01
   0.212500E 02  0.204000E 01  0.890000E 00  0.100009E 01  0.999392E 00  1.000000E 00  0.100043E 01  0.518668E 03
   0.534100E 02  0.228000E 01  0.900000E 00  0.100003E 01  0.100033E 01  0.100000E 01  0.790034E 00  0.652249E 03
  -0.000000E-19 -0.000000E-19 -0.000000E-19 -0.000000E-19  0.135421E 04  0.400000E-01 -0.000000E-19 -0.000000E-19
  -0.000000E-19 -0.000000E-19 -0.000000E-19 -0.000000E-19  0.301733E 04  0.400000E-01 -0.000000E-19 -0.000000E-19
   0.206196E 01  0.424506E 01  0.630701E 01  0.630701E 01  0.279601E 01  0.279601E 01 -0.000000E-19 -0.000000E-19
   0.180000E 01  0.412986E-00  0.985000E 00  0.985000E 00 -0.000000E-19 -0.000000E-19 -0.000000E-19 -0.000000E-19

   0.518670E 03  0.100000E 01  0.123918E 03  0.159103E 01  0.518668E 03  0.100000E 01  0.123918E 03  0.159103E 01
   0.652249E 03  0.200000E 01  0.155962E 03  0.159846E 01  0.116209E 04  0.120000E 02  0.281578E 03  0.161753E 01
   0.240000E 04  0.114004E 02  0.633126E 03  0.182714E 01  0.192492E 04  0.422944E 01  0.494673E 03  0.183080E 01
   0.165352E 04  0.210630E 01  0.418443E 03  0.183597E 01  0.            0.375000E 01  0.750000E 00  0.
   1.000000E 00  0.200000E 01  0.650000E 00  0.180000E 03  0.180000E 03  0.712500E 02  0.726636E 02  0.198399E-01
   0.891739E 00  0.600000E 01  0.830000E 00  0.421627E 02  0.750000E 02  0.988000E 00  0.500000E-01  0.
   0.204000E 01  0.890000E 00  0.540230E-01  0.129655E 03  0.300000E 01  0.756636E 02  0.190383E-01  0.111699E 04
   0.228000E 01  0.900000E 00  0.396015E-01  0.762299E 02  0.            0.756636E 02  0.190383E-01  0.
   0.            0.            0.100000E 01  0.833333E 00  1.000000E 02  0.814598E 00  1.000000E 02  0.141359E 01
   0.212500E 02  0.534100E 02  0.            0.500000E-01  0.200000E-00  0.            0.800000E 00  0.

   0.100000E 01  0.180000E 03  0.750000E 02  0.            0.750000E 00  0.281578E 03  0.            0.
   0.652249E 03  0.200000E 01  0.155962E 03  0.159846E 01  0.655951E 03  0.200000E 01  0.156853E 03  0.159983E 01
   0.655951E 03  0.192000E 01  0.156852E 03  0.160262E 01  0.655951E 03  0.192000E 01  0.156852E 03  0.160262E 01
   0.            0.            0.            0.            0.            0.            0.            0.
   0.105750E 03  0.            0.105750E 03  0.            0.            0.400000E-01  0.140000E 01  0.
   0.            0.            0.            0.            0.            0.            0.            0.

   0.165352E 04  0.210630E 01  0.418443E 03  0.183597E 01  0.655951E 03  0.192000E 01  0.156852E 03  0.160262E 01
   0.141359E 01  0.756636E 02  0.190383E-01  0.            0.105750E 03  0.            0.100000E 01  0.
   0.109311E 04  0.198783E 01  0.265954E 03  0.172707E 01  0.109311E 04  0.190831E 01  0.265954E 03  0.172987E 01
   0.109311E 04  0.190831E 01  0.265954E 03  0.172987E 01  0.109311E 04  0.190831E 01  0.265954E 03  0.172987E 01
   0.181414E 03  0.            0.181414E 03  0.785329E-02  0.            0.400000E [illegible]  0.792807E 03  0.217858E 03
   0.189900E 01  0.412421E 03  0.258767E-00  0.107860E 04  0.181621E 01  0.430890E 03  0.270416E-00  0.174149E-00
   0.919679E 03  0.101949E 01  0.147629E 04  0.100000E 01  0.919679E 03  0.101545E 01  0.147629E 04  0.100000E 01
   0.            0.            0.            0.            0.145410E 04  0.819921E 04  0.            0.115346E 03
   0.819921E 04  0.115346E 03  0.141359E 01  0.181414E 03  0.785329E-02  0.831455E 04  0.831455E 04  0.612051E 00
```

SLS IDLE

OUTPUT

AM= 0. ALTP= 0. T4= 1750.00 ETAR= 1.0000

PCNF 0.561653E 02	CNF 0.561653E 00	ZF 0.594640E 00	PRF 0.126328E 01	WAFC 0.963760E 02	WAF 0.963760E 02
PCNC 0.714378E 02	CNC 0.685858E 00	ZC 0.690779E 00	PRC 0.364504E 01	WACC 0.281215E 02	WAC 0.340180E 02
T2 0.51 468E 03	P2 0.100000E 01	T21 0.562700E 03	P21 0.126328E 01	T3 0.895964E 03	P3 0.460470E 01
PCBLF 0.	BLF 0.	PCBLC 0.500000E-01	BLC 0.170090E 01	PCBLOB 0.	BLOB 0.
PCBLHP 0.800000E 00	BLHP 0.136072E 01	PCBLLP 0.	BLLP 0.	T4 0.175000E 04	P4 0.436574E 01
WA3 0.323171E 02	WFB 0.418316E-00	W04 0.327354E 02	FAR4 0.129441E-01	ETAB 0.965372E 00	DPCOM 0.518946E-01
TFFHP 0.213719E 02	CNHP 0.170665E 01	DHTCHP 0.477920E-01	DHTC 0.838744E 02	T5 0.142146E 04	P5 0.179497E 01
TFFLP 0.486710E 02	CNLP 0.149019E 01	DHTCLP 0.209477E-01	DHTF 0.298027E 02	T55 0.130893E 04	P55 0.124970E 01
PCBLDU 0.200000E-00	BLDU 0.340180E-00	T24 0.564527E 03	P24 0.121928E 01	T25 0.564527E 03	P25 0.121928E 01
WAD 0.626982E 02	WFD 0.	W024 0.626982E 02	FAR24 0.	ETAD 0.	DPDUC 0.348316E-01
ETAF 0.813299E 00	ETAC 0.747810E 00	ETATHP 0.876818E 00	ETATLP 0.884124E 00	AM55 0.260566E-00	AM25 0.149993E-00
T6 0.836140E 03	P6 0.122987E 01	PS6 0.119935E 01	AM6 0.190491E-00	V6 0.267904E 03	W06 0.967944E 02
T7 0.836140E 03	WFA 0.	WG7 0.967944E 02	FAR7 0.434046E-02	ETAA 0.	DPAFT 0.301695E-01
PS8 0.100000E 01	AM8 0.504652E 00	V8 0.695767E 03	PS9 0.100000E 01	AM9 0.504652E 00	V9 0.695767E 03
PS28 0.	AM28 0.	V28 0.	PS29 0.	AM29 0.	V29 0.
BYPASS 0.183309E 01	HPEXT 0.	WFT 0.418316E-00	WGT 0.967944E 02	VA 0.	FRO 0.
CVMNOZ 0.984000E 00	VJM 0.605330E 03	CVDNOZ 0.985000E 00	VJD 0.	FGM 0.206179E 04	FGP 0.

MAIN SUBSONIC CONVERG. NOZZLE FG= 2061.79 FN= 2061.79 SFC= 0.73040

SLS MILITARY

```
OUTPUT          AM=  0.          ALTP=      0.          T4= 2400.00                        ETAR= 1.0000

                PCNF             CNF              ZF               PRF              WAFC             WAF
                1.0000000D 02    1.0000000D 00    0.8333333D 00    0.2000000D 01    0.1800000D 03    0.1800000D 03

                PCNC             CNC              ZC               PRC              WACC             WAC
                1.0000000D 02    0.8917390D 00    0.8145980D 00    0.6000000D 01    0.4216270D 02    0.7500000D 02

                T2               P2               T21              P21              T3               P3
                0.5186680D 03    0.1000000D 01    0.6522490D 03    0.2000000D 01    0.1162090D 04    0.1200000D 02

                PCBLF            BLF              PCBLC            BLC              PCBLOB           BLOB
                0.               0.               0.5000000D-01    0.3750000D 01    0.               0.

                PCBLHP           BLHP             PCBLLP           BLLP             T4               P4
                0.8000000D 00    0.3000000D 01    0.               0.               0.2400000D 04    0.1140900D 02

                WA3              WFB              WG4              FAR4             ETAB             DPCOM
                0.7125000D 02    0.1413590D 01    0.7266360D 02    0.1983990D-01    0.9850000D 00    0.5000000D-01

                TFFHP            CNHP             DHTCHP           DHTC             T5               P5
                0.2125000D 02    0.2040000D 01    0.5402300D-01    0.1296550D 03    0.1924920D 04    0.4329440D 01

                TFFLP            CNLP             DHTCLP           DHTF             T55              P55
                0.5341000D 02    0.2280000D 01    0.3960150D-01    0.7622990D 02    0.1653520D 04    0.2106300D 01

                PCBLDU           BLDU             T24              P24              T25              P25
                0.2000000D-00    0.7500000D 00    0.6559510D 03    0.1920000D 01    0.6559510D 03    0.1920000D 01

                WAD              WFD              WG24             FAR24            ETAD             DPDUC
                0.1057500D 03    0.               0.1057500D 03    0.               0.               0.4000000D-01

                ETAF             ETAC             ETATHP           ETATLP           AM55             AM25
                0.8500000D 00    0.8300000D 00    0.8900000D 00    0.9000000D 00    0.4120240D-00    0.1741340D-00

                T6               P6               PS6              AM6              V6               WG6
                0.1093110D 04    0.1988700D 01    0.1899920D 01    0.2586440D-00    0.4122270D 03    0.1814140D 03

                T7               WFA              WG7              FAR7             ETAA             DPAFT
                0.1093110D 04    0.               0.1814140D 03    0.7853290D-02    0.               0.3798250D-01

                PS8              AM8              V8               PS9              AM9              V9
                0.1019490D 01    0.1000000D 01    0.1476290D 04    0.1019490D 01    0.1000000D 01    0.1476290D 04

                PS28             AM28             V28              PS29             AM29             V29
                0.               0.               0.               0.               0.               0.

                BYPASS           HPEXT            WFT              WGT              VA               FRD
                0.1400000D 01    0.               0.1413590D 01    0.1814140D 03    0.               0.

                CVMNOZ           VJM              CVDNOZ           VJD              FGM              FGP
                0.9850000D 00    0.1454150D 04    0.9850000D 00    0.               0.8199210D 04    0.1153450D 03
MAIN SONIC CONVERGENT NOZZLE     FG=  8314.55                      FN=  8314.55                      SFC= 0.61205
```

SLS TAKE-OFF

NOZZLE DESIGN A8= 0.603242208E 01 AM8= 0.904082228E 00 A9= 0.603242208E 01 AM9= 0.904082228E 00

OUTPUT AM= 0. ALTP= 0. T4= 2400.00 T7= 3200.00 ETAR= 1.0000

PCNF	CNF	ZF	PRF	WAFC	WAF
1.000000E 02	1.000000E 00	0.833333E 00	0.200000E 01	0.180000E 03	0.180000E 03
PCNC	CNC	ZC	PRC	WACC	WAC
1.000000E 02	0.891739E 00	0.81459[illegible] 00	0.600000E 01	0.421627E 02	0.750000E 02
T2	P2	T21	P21	T3	P3
0.518668E 03	0.100000E 01	0.652249E 03	0.200000E 01	0.116209E 04	0.120000E 02
PCBLF	BLF	PCBLC	BLC	PCBLOB	BLOB
0.	0.	0.500000E-01	0.375000E 01	0.	0.
PCBLHP	BLHP	PCBLLP	BLLP	T4	P4
0.800000E 00	0.300000E 01	0.	0.	0.240000E 04	0.114000E 02
WA3	WFB	W04	FAR4	ETAB	DPCOM
0.712500E 02	0.141359E 01	0.726636E 02	0.198399E-01	0.985000E 00	0.500000E-01
TFFHP	CNHP	DHTCHP	DHTC	T5	P5
0.212500E 02	0.204000E 01	0.540230E-01	0.129655E 03	0.192492E 04	0.422944E 01
TFFLP	CNLP	DHTCLP	DHTF	T55	P55
0.534100E 02	0.228000E 01	0.396015E-01	0.762299E 02	0.165352E 04	0.210630E 01
PCBLOU	BLOU	T24	P24	T25	P25
0.200000E-00	0.750000E 00	0.655951E 03	0.192000E 01	0.655951E 03	0.192000E 01
WAD	WFD	W024	FAR24	ETAD	DPDUC
0.105750E 03	0.	0.105750E 03	0.	0.	0.400000E-01
ETAF	ETAC	ETATHP	ETATLP	AM55	AM25
0.850000E 00	0.830000E 00	0.890000E 00	0.900000E 00	0.412024E-00	0.174134E-00
T6	P6	PS6	AM6	V6	W06
0.109311E 04	0.198870E 01	0.189992E 01	0.258644E-00	0.412227E 03	0.181414E 03
T7	WFA	W07	FAR7	ETAA	DPAFT
0.320000E 04	0.705234E 01	0.188466E 03	0.470330E-01	0.910000E 00	0.399025E-01
PS8	AM8	V8	PS9	AM9	V9
0.100000E 01	0.904082E 00	0.227120E 04	0.100000E 01	0.904082E 00	0.227120E 04
PS28	AM28	V28	PS29	AM29	V29
0.	0.	0.	0.	0.	0.
BYPASS	HPEXT	WFT	WOT	VA	FRD
0.140000E 01	0.	0.846593E 01	0.188466E 03	0.	0.
CVMNOZ	VJM	CVDNOZ	VJD	FGM	FGP
0.985000E 00	0.223713E 04	0.985000E 00	0.	0.131044E 0[illegible]	0.

MAIN SUBSONIC CONVERG. NOZZLE FG= 13104.42 FN= 13104.42 SFC= 2.32573

SET-UP LOW ALTITUDE DASH

```
OUTPUT              AM=  1.200      ALTP=   500.         T4= 2400.00                        ETAR= 0.9915
                  PCNF           CNF            ZF             PRF            WAFC           WAF
                0.834554E 02   0.736546E 00   0.495935E-00   0.136065E 01   0.134829E 03   0.281071E 03
                  PCNC           CNC            ZC             PRC            WACC           WAC
                0.922888E 02   0.772037E 00   0.737459E 00   0.443942E 01   0.333410E 02   0.894058E 02
                  T2             P2             T21            P21            T3             P3
                0.665884E 03   0.236205E 01   0.741158E 03   0.321391E 01   0.122567E 04   0.142679E 02
                  PCBLF          BLF            PCBLC          BLC            PCBLOB         BLOB
                0.             0.             0.500000E-01   0.447029E 01   0.             0.
                  PCBLHP         BLHP           PCBLLP         BLLP           T4             P4
                0.800000E 00   0.357623E 01   0.             0.             0.240000E 04   0.135333E 02
                  WA3            WFB            WG4            FAR4           ETAB           DPCOM
                0.849355E 02   0.160384E 01   0.865394E 02   0.188830E-01   0.985000E 00   0.514829E-01
                  TFFHP          CNHP           DHTCHP         DHTC           T5             P5
                0.213285E 02   0.188269E 01   0.517902E-01   0.124323E 03   0.194440E 04   0.521690E 01
                  TFFLP          CNLP           DHTCLP         DHTF           T55            P55
                0.518314E 02   0.189323E 01   0.290705E-01   0.566956E 02   0.174336E 04   0.315748E 01
                  PCBLOU         BLOU           T24            P24            T25            P25
                0.200000E-00   0.894058E 00   0.743465E 03   0.305882E 01   0.743465E 03   0.305882E 01
                  WAD            WFD            WG24           FAR24          ETAD           DPDUC
                0.192559E 03   0.             0.192559E 03   0.             0.             0.482542E-01
                  ETAF           ETAC           ETATHP         ETATLP         AM55           AM25
                0.808624E 00   0.780989E 00   0.883980E 00   0.898787E 00   0.324506E-00   0.214069E-00
                  T6             P6             PS6            AM6            V6             WG6
                0.108126E 04   0.308046E 01   0.295119E 01   0.257827E-00   0.409007E 03   0.282675E 03
                  T7             WFA            WG7            FAR7           ETAA           DPAFT
                0.108126E 04   0.             0.282675E 03   0.570616E-02   0.             0.398977E-01
                  PS8            AM8            V8             PS9            AM9            V9
                0.157801E 01   0.100000E 01   0.146867E 04   0.157801E 01   0.100000E 01   0.146867E 04
                  PS28           AM28           V28            PS29           AM29           V29
                0.             0.             0.             0.             0.             0.
                  BYPASS         HPEXT          WFT            WGT            VA             FRD
                0.214377E 01   0.             0.160384E 01   0.282675E 03   0.133809E 04   0.116895E 05
                  CVMNOZ         VJM            CVDNOZ         VJD            FGM            FGP
                0.985000E 00   0.144664E 04   0.985000E 00   0.             0.127099E 05   0.352618E 04
MAIN SONIC CONVERGENT NOZZLE   FG= 16236.07                 FN=  4546.59                    SFC= 1.26992
```

LOW ALTITUDE DASH

NOZZLE DESIGN A8= 0.59879597E 01 AM8= 0.09999999E 01 A9= 0.59879597E 01 AM9= 0.09999999E 01

OUTPUT AM= 1.200 ALTP= 500. T4= 2400.00 T7= 3200.00 ETAR= 0.9915

PCNF	CNF	ZF	PRF	WAFC	WAF
0.834554E 02	0.736546E 00	0.495935E-00	0.136065E 01	0.134829E 03	0.281071E 03
PCNC	CNC	ZC	PRC	WACC	WAC
0.922888E 02	0.772037E 00	0.737459E 00	0.443942E 01	0.333410E 02	0.894058E 02
T2	P2	T21	P21	T3	P3
0.665884E 03	0.236205E 01	0.741158E 03	0.321391E 01	0.122567E 04	0.142679E 02
PCBLF	BLF	PCBLC	BLC	PCBLOB	BLOB
0.	0.	0.500000E-01	0.447029E 01	0.	0.
PCBLHP	BLHP	PCBLLP	BLLP	T4	P4
0.800000E 00	0.357623E 01	0.	0.	0.240000E 04	0.135333E 02
WA3	WFB	WG4	FAR4	ETAB	DPCOM
0.849355E 02	0.160384E 01	0.865394E 02	0.188830E-01	0.985000E 00	0.514829E-01
TFFHP	CNHP	DHTCHP	DHTC	T5	P5
0.213285E 02	0.188269E 01	0.517902E-01	0.124323E 03	0.194440E 04	0.521690E 01
TFFLP	CNLP	DHTCLP	DHTF	T55	P55
0.518314E 02	0.189323E 01	0.290705E-01	0.566956E 02	0.174336E 04	0.315748E 01
PCBLDU	BLDU	T24	P24	T25	P25
0.200000E-00	0.894058E 00	0.743465E 03	0.305882E 01	0.743465E 03	0.305882E 01
WAD	WFD	WG24	FAR24	ETAD	DPDUC
0.192559E 03	0.	0.192559E 03	0.	0.	0.482542E-01
ETAF	ETAC	ETATHP	ETATLP	AM55	AM25
0.808626E 00	0.780989E 00	0.883980E 00	0.898787E 00	0.324506E-00	0.214069E-00
T6	P6	PS6	AM6	V6	WG6
0.108126E 04	0.308846E 01	0.295119E 01	0.257827E-00	0.409007E 03	0.282675E 03
T7	WFA	WG7	FAR7	ETAA	DPAFT
0.320000E 04	0.110545E 02	0.293729E 03	0.450361E-01	0.910000E 00	0.398977E-01
PS8	AM8	V8	PS9	AM9	V9
0.140201E 01	0.100000E 01	0.248577E 04	0.140201E 01	0.100000E 01	0.248577E 04
PS28	AM28	V28	PS29	AM29	V29
0.	0.	0.	0.	0.	0.
BYPASS	HPEXT	WFT	WGT	VA	FRD
0.214377E 01	0.	0.126583E 02	0.293729E 03	0.133009E 04	0.116895E 05
CVHNOZ	VJM	CVDNOZ	VJD	FGM	FGP
0.985000E 00	0.244848E 04	0.985000E 00	0.	0.223532E 05	0.532154E 04

MAIN SONIC CONVERGENT NOZZLE FG= 27674.70 FN= 15905.22 SFC= 2.05076

SUBSONIC CRUISE

OUTPUT   AM= 0.800   ALTP= 36100.   T4= 2100.00   ETAR= 1.0000

PCNF	CNF	ZF	PRF	WAFC	WAF
0.931973E 02	0.101117E 01	0.844335E 00	0.203907E 01	0.102658E 03	0.674923E 02
PCNC	CNC	ZC	PRC	WACC	WAC
0.933169E 02	0.898860E 00	0.821996E 00	0.613264E 01	0.428058E 02	0.285406E 02
T2	P2	T21	P21	T3	P3
0.440068E 03	0.340355E-00	0.559018E 03	0.694000E 00	0.101032E 04	0.425610E 01
PCBLF	BLF	PCBLC	BLC	PCBLOB	BLOB
0.	0.	0.500000E-01	0.142703E 01	0.	0.
PCBLHP	BLHP	PCBLLP	BLLP	T4	P4
0.800000E 00	0.114163E 01	0.	0.	0.210000E 04	0.404321E 01
WA3	WFB	WG4	FAR4	ETAB	DPCOM
0.271136E 02	0.458883E-00	0.275725E 02	0.169245E-01	0.980787E 00	0.500209E-01
TFFHP	CNHP	DHTCHP	DHTC	T5	P5
0.212556E 02	0.203510E 01	0.541625E-01	0.113732E 03	0.167224E 04	0.148928E 01
TFFLP	CNLP	DHTCLP	DHTF	T55	P55
0.535024E 02	0.227979E 01	0.401773E-01	0.669031E 02	0.142664E 04	0.733033E 00
PCBLDU	BLDU	T24	P24	T25	P25
0.200000E-00	0.285406E-00	0.562353E 03	0.666524E 00	0.562353E 03	0.666524E 00
WAD	WFD	WG24	FAR24	ETAD	DPDUC
0.392371E 02	0.	0.392371E 02	0.	0.	0.396014E-01
ETAF	ETAC	ETATHP	ETATLP	AM55	AM25
0.837913E 00	0.828109E 00	0.889306E 00	0.897883E 00	0.416152E-00	0.172107E-00
T6	P6	PS6	AM6	V6	WG6
0.942355E 03	0.691392E 00	0.660512E 00	0.257763E-00	0.382779E 03	0.679512E 02
T7	WFA	WG7	FAR7	ETAA	DPAFT
0.942355E 03	0.	0.679512E 02	0.679905E-02	0.	0.399961E-01
PS8	AM8	V8	PS9	AM9	V9
0.352897E-00	0.100000E 01	0.137217E 04	0.352897E-00	0.100000E 01	0.137217E 04
PS28	AM28	V28	PS29	AM29	V29
0.	0.	0.	0.	0.	0.
BYPASS	HPEXT	WFT	WGT	VA	FRD
0.136478E 01	0.	0.458883E-00	0.679512E 02	0.774794E 03	0.162531E 04
CVMNOZ	VJM	CVDNOZ	VJD	FGM	FGP
0.985000E 00	0.135159E 04	0.985000E 00	0.	0.285454E 04	0.767144E 03

MAIN SONIC CONVERGENT NOZZLE   FG= 3621.69   FN= 1996.38   SFC= 0.82749

SUPERSONIC AT MILITARY POWER

OUTPUT AM= 1.200 ALTP= 50000. T4= 2400.00 ETAR= 0.9915

PCNF	CNF	ZF	PRF	WAFC	WAF
0.100191E 03	0.101769E 01	0.855547E 00	0.206600E 01	0.183700E 03	0.513534E 02
PCNC	CNC	ZC	PRC	WACC	WAC
0.100012E 03	0.898871E 00	0.822625E 00	0.613671E 01	0.428047E 02	0.218175E 02
T2	P2	T21	P21	T3	P3
0.502712E 03	0.275217E-00	0.642096E 03	0.568597E 00	0.115396E 04	0.348932E 01
PCBLF	BLF	PCBLC	BLC	PCBLOB	BLOB
0.	0.	0.500000E-01	0.109088E 01	0.	0.
PCBLHP	BLHP	PCBLLP	BLLP	T4	P4
0.800000E 00	0.872700E 00	0.	0.	0.240000E 04	0.331539E 01
WA3	WFB	W04	FAR4	ETAB	DPCOM
0.207265E 02	0.417850E-00	0.211445E 02	0.201600E-01	0.975313E 00	0.498460E-01
TFFHP	CNHP	DHTCHP	DHTC	T5	P5
0.212515E 02	0.204025E 01	0.541369E-01	0.130008E 03	0.192371E 04	0.122601E 01
TFFLP	CNLP	DHTCLP	DHTF	T55	P55
0.535156E 02	0.228507E 01	0.403960E-01	0.779472E 02	0.164620E 04	0.598571E 00
PCBLDU	BLDU	T24	P24	T25	P25
0.200000E-00	0.218175E-00	0.645937E 03	0.546261E 00	0.645937E 03	0.546261E 00
WAD	WFD	W024	FAR24	ETAD	DPDUC
0.297541E 02	0.	0.297541E 02	0.	0.	0.592836E-01
ETAF	ETAC	ETATHP	ETATLP	AM55	AM25
0.830473E 00	0.827917E 00	0.889763E 00	0.897465E 00	0.423142E-00	0.170750E-00
T6	P6	PS6	AM6	V6	WG6
0.109268E 04	0.565981E 00	0.540578E 0	0.259374E-00	0.413274E 03	0.517713E 02
T7	WFA	WG7	FAR7	ETAA	DPAFT
0.109268E 04	0.	0.517713E 02	0.813675E-02	0.	0.400840E-01
PS8	AM8	V8	PS9	AM9	V9
0.290912E-00	0.100000E 01	0.147597E 04	0.290912E-00	0.100000E 01	0.147597E 04
PS28	AM28	V28	PS29	AM29	V29
0.	0.	0.	0.	0.	0.
BYPASS	HPEXT	WFT	WGT	VA	FRD
0.135377E 01	0.	0.417850E-00	0.517713E 02	0.116219E 04	0.185499E 04
CVMNOZ	VJM	CVDNOZ	VJD	FGM	FGP
0.985000E 00	0.145383E 04	0.985000E 00	0.	0.233936E 04	0.104409E 04

MAIN SONIC CONVERGENT NOZZLE FG= 3383.44 FN= 1520.45 SFC= 0.98417

SET-UP SUPERSONIC WITH AFTERBURNER

OUTPUT

AM= 1.600 ALTP= 50000. T4= 2400.00 ETAR= 0.9624

PCNF 0.905133E 02	CNF 0.848444E 00	ZF 0.585574E 00	PRF 0.162549E 01	WAFC 0.153578E 03	WAF 0.673905E 02
PCNC 0.970176E 02	CNC 0.838545E 00	ZC 0.780663E 00	PRC 0.529237E 01	WACC 0.380951E 02	WAC 0.249891E 02
T2 0.590294E 03	P2 0.468120E-00	T21 0.694285E 03	P21 0.760924E 00	T3 0.119781E 04	P3 0.399665E 01
PCBLF 0.	BLF 0.	PCBLC 0.500000E-01	BLC 0.124945E 01	PCBLOB 0.	BLOB 0.
PCBLHP 0.800000E 00	BLHP 0.999563E 00	PCBLLP 0.	BLLP 0.	T4 0.240000E 04	P4 0.379869E 01
WA3 0.237896E 02	WFB 0.459302E-00	HO4 0.241989E 02	FAR4 0.193475E-01	ETAB 0.982742E 00	DPCOM 0.507829E-01
TFFHP 0.212863E 02	CNHP 0.197716E 01	DHTCHP 0.535433E-01	DHTC 0.128631E 03	T5 0.192924E 04	P5 0.141463E 01
TFFLP 0.532579E 02	CNLP 0.206139E 01	DHTCLP 0.346163E-01	DHTF 0.664961E 02	T55 0.169141E 04	P55 0.772359E 00
PCBLDU 0.200000E-00	BLDU 0.249891E-00	T24 0.697309E 03	P24 0.727656E 00	T25 0.697309E 03	P25 0.727656E 00
WAD 0.426513E 02	WFD 0.	HO24 0.426513E 02	FAR24 0.	ETAD 0.	DPDUC 0.437198E-01
ETAF 0.844790E 00	ETAC 0.807461E 00	ETATHP 0.887090E 00	ETATLP 0.897886E 00	AM55 0.372028E-00	AM25 0.191841E-00
T6 0.108670E 04	P6 0.743217E 00	PS6 0.710188E 00	AM6 0.257923E-00	V6 0.410036E 03	HO6 0.678498E 02
T7 0.108670E 04	WFA 0.	HO7 0.678498E 02	FAR7 0.681552E-02	ETAA 0.	DPAFT 0.398956E-01
PS8 0.379947E-00	AM8 0.100000E 01	V8 0.147216E 04	PS9 0.379947E-00	AM9 0.100000E 01	V9 0.147216E 04
PS28 0.	AM28 0.	V28 0.	PS29 0.	AM29 0.	V29 0.
BYPASS 0.169680E 01	HPEXT 0.	WFT 0.459302E-00	HOT 0.678498E 02	VA 0.154959E 04	FRD 0.324571E 04
CVMNOZ 0.985000E 00	VJM 0.145007E 04	CVDNOZ 0.985000E 00	VJD 0.	FGM 0.305797E 04	FGP 0.157090E 04

MAIN SONIC CONVERGENT NOZZLE FG= 4628.87 FN= 1383.16 SFC= 1.19544

SUPERSONIC PARTIAL A/B

NOZZLE DESIGN   A8= 0.3657000E 01   AM8= 0.0999999E 01   A9= 0.3657003E 01   AM9= 0.0999999E 01

OUTPUT   AM= 1.600   ALT/= 50000.   T4= 3400.00   T7= 1700.00   CSAR= 0.9624

PCNF	CNF	ZF	PRF	WAFC	WAF
0.905133E 02	0.848644E 00	0.685574E 00	0.162549E 01	0.153570E 03	0.673905E 02
PCNC	CNC	ZC	PRC	WACC	WAC
0.970176E 02	0.838545E 00	0.780663E 00	0.525237E 01	0.380951E 02	0.249891E 02
T2	P2	T21	P21	T3	P3
0.590294E 03	0.468120E-00	0.694285E 03	0.760924E 00	0.119781E 04	0.399665E 01
PCBLP	BLP	PCBLC	BLC	PCBLOB	BLOB
0.	0.	0.500000E-01	0.124949E 01	0.	0.
PCBLHP	BLHP	PCBLLP	BLLP	T4	P4
0.800000E 00	0.999564E 00	0.	0.	0.240000E 04	0.379369E 01
WA3	WFB	WG4	FAR4	ETAB	DPCOM
0.237396E 02	0.459302E-00	0.241909E 02	0.193475E-01	0.982742E 00	0.507829E-01
TPPHP	CNHP	DHTCHP	DHTC	T5	P5
0.212063E 02	0.197916E 01	0.555433E-01	0.129631E 03	0.192924E 04	0.141463E 01
TPPLP	CNLP	DHTCLP	DHTP	T55	P55
0.532979E 02	0.206139E 01	0.346163E-01	0.666961E 02	0.169141E 04	0.772359E 00
PCBLOU	BLOU	T24	P24	T25	P25
0.200000E-00	0.249891E-00	0.697309E 03	0.727696E 00	0.697309E 03	0.727696E 00
WAD	WFD	WG24	FAR24	ETAD	DPDUC
0.426913E 02	0.	0.426913E 02	0.	0.	0.437198E-01
ETAF	ETAC	ETATHP	ETATLP	AM55	AM25
0.844790E 00	0.807461E 00	0.887090E 00	0.897806E 00	0.372020E-00	0.191841E-00
T6	P6	PS6	AM6	V6	WG6
0.108670E 04	0.743217E 00	0.710180E 00	0.257923E-00	0.410035E 03	0.678490E 02
T7	WFA	WG7	FAR7	ETAA	DPAFT
0.170000E 04	0.645574E 00	0.684954E 02	0.163951E-01	0.940000E 00	0.398956E-01
PS8	AM8	V8	PS9	AM9	V9
0.375574E-00	0.100000E 01	0.183105E 04	0.375574E-00	0.100000E 01	0.185105E 04
PS28	AM28	V28	PS29	AM29	V29
0.	0.	0.	0.	0.	0.
BYPASS	HPEXT	WAT	WGT	VA	FRD
0.169600E 01	0.	0.110480E 01	0.684954E 02	0.154959E 04	0.324571E 04
CVMNOZ	VJM	CVDNOZ	VJD	FGM	FGP
0.985000E 00	0.180350E 04	0.985000E 00	0.	0.303965E 04	0.202080E 04

MAIN SONIC CONVERGENT NOZZLE   FG= 5060.45   FN= 2614.74   SFC= 1.52171

SUPERSONIC FULL A/B

NOZZLE DESIGN   A8= 0.5961271E 01   AM8= 0.09999999E 01   A9= 0.5961271E 01   AM9= 0.09999999E 01

OUTPUT   AM= 1.600   ALTP= 50000.   T4= 2400.00   T7= 3200.00   ETAR= 0.9624

PCNP 0.9051336E 02	CNP 0.8484440E 00	ZP 0.6855740E 00	PRP 0.1625490E 01	WAPC 0.1535700E 03	WAP 0.6739050E 02
PCNC 0.9701760E 02	CNC 0.8385450E 00	ZC 0.7606630E 00	PRC 0.5252370E 01	WACC 0.3009510E 02	WAC 0.2498910E 02
T2 0.5902940E 03	P2 0.4681200E-00	T21 0.6942850E 03	P21 0.7609240E 00	T3 0.1197810E 04	P3 0.3996650E 01
PCBLP 0.	BLP 0.	PCBLC 0.5000000E-01	BLC 0.1249450E 01	PCBLOB 0.	BLOB 0.
PCBLHP 0.0000000E 00	BLHP 0.9995630E 00	PCBLLP 0.	BLLP 0.	T4 0.2400000E 04	P4 0.3793690E 01
WA3 0.2373960E 02	WFB 0.4593020E-00	WG4 0.2419890E 02	FAR4 0.1934150E-01	ETAB 0.9827420E 00	DPCOM 0.5078290E-01
TPRHP 0.2128630E 02	CNHP 0.1979160E 01	DHTCHP 0.5354330E-01	DHTC 0.1286310E 03	T5 0.1929240E 04	P5 0.1414630E 01
TPRLP 0.5328790E 02	CNLP 0.2061390E 01	DHTCLP 0.3461630E-01	DHTF 0.6689610E 02	T55 0.1691410E 04	P55 0.7723590E 00
PCBLOU 0.2000000E-00	BLOU 0.2408910E-00	T24 0.6973090E 03	P24 0.7276560E 00	T25 0.6973090E 03	P25 0.7276560E 00
WAD 0.4265130E 02	WFD 0.	WG24 0.4265130E 02	FAR24 0.	ETAD 0.	DPDUC 0.4371980E-01
ETAP 0.8447900E 00	ETAC 0.8074610E 00	ETATHP 0.8870900E 00	ETATLP 0.8978860E 00	AM55 0.3720280E-00	AM25 0.1910410E-00
T6 0.1086700E 04	P6 0.7432170E 00	PS6 0.7101880E 00	AM6 0.3579230E-00	V6 0.4100350E 03	WG6 0.6784980E 02
T7 0.3200000E 04	WFA 0.2646040E 01	WG7 0.7049580E 02	FAR7 0.4607970E-01	ETAA 0.9100000E 00	DPAFT 0.3989560E-01
PS8 0.3301290E-00	AM8 0.1000000E 01	V8 0.2485540E 04	PS9 0.3301290E-00	AM9 0.1000000E 01	V9 0.2485540E 04
PS28 0.	AM28 0.	V28 0.	PS29 0.	AM29 0.	V29 0.
BYPASS 0.1696800E 01	HPEXT 0.	WFT 0.3100340E 01	WGT 0.7049530E 02	VA 0.1549590E 04	FRD 0.3245710E 04
CVHNOZ 0.9850000E 00	VJH 0.2446262E 04	CVDNOZ 0.9850000E 00	VJD 0.	FGM 0.5364320E 04	FGP 0.2821720E 04

MAIN SONIC CONVERGENT NOZZLE   FG= 8186.04   FN= 4940.33   SFC= 2.26285

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4 DESCRIPTIVE NOTES (Type of report and inclusive dates)	
5 AUTHOR(S) (Last name, first name, initial) McKinney, John S. Captain, USAF	
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11 SUPPLEMENTARY NOTES	12 SPONSORING MILITARY ACTIVITY Air Force Aero Propulsion Laboratory Wright-Patterson Air Force Base, Ohio 45433

13 ABSTRACT

This report describes a digital computer program titled SMOTE (Simulation of Turbofan Engine). SMOTE is a computer program for balancing-cycle turbofan engines capable of running both design and off-design points. Component performance maps are reduced to Block Data (tabular form) to provide a base for calculating component performance. The design point is run first and map correction factors are calculated to scale the components to the desired performance. These correction factors are then applied to the component performance maps at off-design points. Initially, when the program is running at an off-design point, the cycle is not balanced, and errors (for example, work required by the compressor minus work supplied by the turbine) are generated. Small changes in engine independent variables (for example, compressor speed) then produce small changes in the errors, and these differential changes are loaded into a matrix. The matrix is then solved for the set of independent variables which results in zero errors, thus balancing the cycle. Actually, this process may be repeated several times before it reaches a balanced point because there is a non linear relationship between the independent variables and the errors. Sample results are included in this report.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Turbine Engine Simulation						
Turbine Engine Computer Programs						
Turbine Engine Cycle Analysis						

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